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Reducing costs of Carbon Capture and Storage by shared reuse of existing pipeline – case study of a CO_2 capture cluster for industry and power in Scotland.

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Keywords:
Carbon capture and storage
Industrial emitters cluster
Carbon dioxide transport
CO_2 pipeline network
Infrastructure reuse
Cost reduction

Highlights:

- Existing pipeline can transport CO_2 from Scottish industry to N. Sea storage sites
- The pipeline capacity can take identified industrial and power CO_2 capture volumes
- Estimated capital costs for industrial capture and pipeline networks are given
- Sharing reuse of existing pipeline reduces capital costs for CCS cluster projects

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Abstract:

The deployment of Carbon Capture and Storage (CCS) is recognised as critical to delivering deep decarbonisation of energy and industrial processes. CCS clusters, where multiple CO_2 emitting sources share CO_2 transport and storage infrastructures, offer cost savings and enable smaller sources to undertake CCS, which are unlikely to be capable of justifying a stand-alone transport and storage system. Scotland has a legacy of onshore and offshore pipelines, which transported methane from producing regions. These can be re-used to connect CO_2 emitters to storage. Approximately 80% of large point-source CO_2 emissions in Scotland are within 40 km of the Feeder 10 pipeline. Thirteen selected emitters are evaluated for potential CO_2 capture volume, estimated capture project cost and cost of connection. Scenarios for sequential deployment show that Feeder 10 has capacity through known expansion potential for developments allowing capture volumes rising from 2 to 8 Mt yr $^{-1}$ CO_2.

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1 Introduction

The target of limiting global mean temperature increase to no more than 2˚C suggests a significant role for Carbon Capture and Storage (CCS). (1),(2) Its application is required to fossil fuel thermal (coal and natural gas) power plant, CO_2 separation in upstream hydrocarbon production, and industrial sources of CO_2 including the manufacture of steel, cement, chemicals and petrochemical refining. (3) Globally, a small number (22 in 2015) of commercial scale CCS projects on power plant, upstream production and industry are in operation or under construction, the majority located in North America. (4)

At present, no commercial-scale CCS projects have commenced construction in the European Union (EU), though two gas processing projects using CCS during hydrocarbon production are in operation offshore of Norway. A small number of proposed CCS projects located around the North Sea are undergoing front-end engineering and design (FEED) work and awaiting financial closure. (5) Some of these projects are in receipt of government funding and support, although capital support for key UK projects has recently (2015) been withdrawn. (6) Public funding support for early projects recognises their role both to develop and demonstrate CCS technology at commercial scale, and to establish transport and storage infrastructure leading to reduced unit costs for subsequent CCS projects as part of a cluster of CO_2 sources making use of shared or paralleled CO_2 transport and storage. (7)

The subsurface of the North Sea offshore of Scotland has extensive CO_2 storage potential in both depleted hydrocarbon fields and saline aquifers. This area holds the largest, best understood and most socially acceptable CO_2 storage capacity in Europe with over 50 billion tonnes capacity, (8) enough for several decades-worth of projected storage requirement for the whole EU. Developing this storage capacity together with infrastructure to access it, therefore, has strategic importance to the UK and the whole of Europe. Although the scale of CO_2 emission in Scotland that might be captured and stored is relatively small in European terms, it is the role in commercialising this storage resource and making it available to other European states that gives the development of a Scottish CCS cluster international significance.

Modelling the cost-optimisation of CO_2 transport demonstrates the cost-savings of shared pipelines. (9),(10),(11) Regional analyses in the UK (12),(13),(14) Netherlands, (15) and France (16) identify the expansion of CCS through the creation of clusters utilising shared transport and storage infrastructure as an efficient and cost-minimising approach to facilitating wider CCS deployment, especially for industry sources of CO_2 with generally lower emission volumes compared to power sources. These findings are evidenced by the recent development of CCS in the southern USA.

The CO_2 enhanced oil recovery (CO_2-EOR) industry in the USA currently operates around 6,000 km of CO_2 pipeline, (17) transporting in the region of 60 million tonnes per year (Mt yr^{-1}) CO_2. (18) This includes a growing network of pipelines along the Gulf Coast, connecting the natural CO_2 reservoir at Jackson Dome, Mississippi, to oilfield operations in Mississippi, Louisiana and Texas. This 'trunk' pipeline system has subsequently been connected into by two projects capturing anthropogenic CO_2: Air Products Port Arthur and PCS Nitrogen, with further projects in active planning. (5) While multiple factors are enabling these projects to proceed (e.g. CO_2 income from sale to CO_2-EOR, government capital grants), the proximity of an existing CO_2 trunk pipeline is a significant contributing element. This relatively straightforward and inexpensive connection to the CO_2 pipeline system (and its market for CO_2) is perhaps a key enabler for smaller scale CCS projects on industrial sources (<1 Mt yr^{-1} CO_2), which produce insufficient quantities of CO_2 to finance individual CO_2 transport solutions. Larger CCS projects (>1 Mt yr^{-1} CO_2), primarily coal power plant and natural gas processing facilities, have a greater potential to be able to finance dedicated pipeline. A similar logic supports the current construction of the 240 km Alberta Carbon Trunk Line, Canada, (19) which is aggregating CO_2 capture opportunities in Edmonton's industrial region for transport to CO_2-EOR operations in south-central Alberta (initially 1.2 Mt yr^{-1} CO_2 from refining (20) and 0.6 Mt yr^{-1} CO_2 from fertiliser production (5)).

Pipelines for CO_2-EOR in North America have been purpose built, but it is also possible, subject to case-specific conditions, to convert natural gas or oil pipelines to carry CO_2. As the output of mature hydrocarbon production regions start to decline, such conversions could present opportunities to re-use redundant oil and gas pipeline capacity for the reverse shipment of CO_2 either for CO_2-EOR or CO_2 storage.

In Scotland, one such opportunity is the Feeder 10 natural gas transmission pipeline (formal asset name No.10 Feeder, described below). This connects the St Fergus gas treatment terminal (Aberdeenshire) via a 280 km onshore route through eastern Scotland to the Avonbridge compressor station (West Lothian), in Scotland's Central Belt. With declining North Sea gas production the capacity of Feeder 10 has become redundant and the pipeline was identified, assessed and costed for CO_2 transport by the proposed UK CCS Competition project at Longannet power plant, which lies close to it (the project was subsequently cancelled in 2011). (21) The route of Feeder 10 also runs close to a number of other operating and proposed power sector and industrial CO_2 emission sources.

1.1 Study aims

This work explores the potential for formation of an industrial capture cluster in Central Scotland and indicates the likely scale of investment required.

The work assesses the potential for the existing Feeder 10 natural gas transmission pipeline in Scotland to facilitate the creation of a CCS cluster by providing a trunk line for CO_2 transport linking existing and planned emitters in the Scottish Central Belt to CO_2 storage offshore North East Scotland.

The study uses publicly available emissions data to determine which industrial point source emitters might be best placed, in terms of location, scale and process type, to participate in a CCS project using Feeder 10 as the transport element. For a selection of example cases, order of magnitude capital cost estimates are made for construction of CO_2 capture units, for connection to existing pipelines and for shared pipeline refurbishment costs.

1.2 Existing pipeline infrastructure

The development of a CCS cluster in Central Scotland could be facilitated by existing pipeline infrastructure that has already been identified and evaluated for CO_2 transport. Feeder 10 is one of three existing high-pressure pipelines used to transport natural gas from the St Fergus gas treatment facilities in North East Scotland to Central Scotland; it forms part of the UK National Transmission System, National Grid's gas network. (22) It ends at the Avonbridge compressor station, 11 km south of the Grangemouth petrochemical complex (Figure 1), where it connects to other pipelines. Due to declining gas transport volumes, Feeder 10 can be made available for future use for CO_2 transport and has been evaluated in detail for this purpose. (21)

Feeder 8 is a similar high-pressure natural gas pipeline running from Avonbridge to Northumberland where it feeds a distribution network. Although currently needed for gas transport, it may be available in future for CO_2 transport and has been included in this analysis where it is closer to emitting sites than Feeder 10. (22)

The use of Feeder 10 was proposed for the Longannet CCS Project; the capital expenditure needed to repurpose the pipeline for CO_2 use was estimated at approximately £80 million, excluding compression. (21) The pipeline's pressure rating constrains it to gas-phase CO_2 transport. In this mode it has capacity to deliver from Central Scotland to St Fergus up to 3.5 Mt yr^{-1} CO_2 with compression only required at the entry point for this capacity. If intermediate compression is added the capacity could be increased; an optimum capacity of around 7 Mt yr $^{-1}$ CO_2 was estimated using two or three booster stations that could be located at existing booster sites. However, the maximum theoretical capacity of 10 Mt yr $^{-1}$ CO_2, requiring further boosting, was thought likely to be economically inefficient compared to a new pipeline specified to carry liquid CO_2, due to increased operating costs from the additional boosters. (23)

1.3 Point-source CO_2 emissions in Scotland - Overview

Total greenhouse-gas (GHG) emissions in Scotland were estimated as 50.5 Mt in 2013, the latest year of consolidated regional and sectorial estimates, with a generally downward trend with time. (24) In recent years, industry sectors with emissions predominantly from large point sources (energy supply, business/industry, industrial process, public institution and waste management) typically make up around 60 % of total GHG emissions, the remainder being from distributed sources (transport, residential, agriculture).

All GHG emissions from large point sources in Scotland are reported to the Scottish Environment Protection Agency (SEPA), which maintains a publicly accessible database, the Scottish Pollutant Release Inventory (SPRI). (25) For CO_2 emissions there is a reporting threshold of 10,000 tonnes per year (t yr $^{-1}$); in 2014, the latest year of data available, the inventory listed eighty-eight CO_2 emission sites above this threshold, totalling 19.1 Mt. (25) These were dominated by emissions from electricity generation (10.2 Mt) but industrial sectors, including refineries and gas processing (3.7 Mt), chemicals (1.9 Mt), pulp, paper and board (1.1 Mt) and inorganic materials (0.8 Mt) also had sizeable emissions.

2 Methods

This analysis was carried out in three stages:

1. SPRI emission data was screened to identify sites with potential for industrial CCS projects based on criteria of CO_2 emission volume (≥ 0.1 Mt yr $^{-1}$), distance from Feeder 8 or 10 and industry type.
2. For these selected sites, an estimate of potential capture rate and an order of magnitude estimate of capital cost for capture plant were made.
3. For these sites, potential routes for connection to Feeder 10 were identified and an order of magnitude capital cost estimate made for these new links.

This analysis was combined with Feeder 10 capacity information to give an overall assessment of the potential to form an industrial CCS cluster in Scotland, based on use of the existing pipeline, and its likely cost.

2.1 Analysis of emission data

CO_2 emission data for 2014, company names and site addresses were extracted from the SPRI database; industry sector, and where appropriate, sub-sector were determined. Accurate locations of emission sources and the routes of Feeders 8 and 10 (22),(26) were plotted on a Google Map; an extract is shown in Figure 1. The perpendicular distance of each emitter from the nearest of these pipelines was measured. The distribution of emissions by scale, by sector and by location relative to the pipelines were determined, allowing selection of potential sites for industrial capture projects that could benefit from re-use of the existing pipelines (described in Sections 3.1 – 3.3).

2.2 Capture rate and capture cost estimates

Capture rates and costs for potential capture projects were estimated with reference to a recent high-level review of CCS costs for UK industry carried out by the consultant Element Energy for the UK Government. (27) The proportion of total emissions available for capture was estimated depending on the complexity of industrial facilities in three bands: combined heat and power (CHP) plant and general industry – 100 %; gas/oil separation and treatment – 75 %; refinery and petrochemicals – 50 %. For each, a general efficiency for amine-solvent post-combustion capture of 90 % was applied leading to overall capture rates of 90 %, 67.5 % and 45 % respectively for the three bands, based on total emissions.

Order of magnitude estimates of capital cost (CAPEX) at the 'total overnight cost' level (28) for potential capture projects were based on the reference case data given in the Element Energy review. (27) 'Total overnight costs' are costs as if the project was completed 'overnight'. They include all project costs, including finance costs and owner's costs, as calculated up to the point of final investment decision, they do not include cost escalation or interest on debt during the capital expenditure period. (28) Costs for the reference cases, for 'N^{th} of a kind' projects, were normalised to a 'Specific CAPEX' per tonne of CO_2 capture capacity, given in Table 1, with units of £ $t(CO_2)^{-1}$ yr (pounds per [tonne CO_2 per year]). No costs were given in the review for capture projects on gas/oil separation and treatment plant, the costs for capture from CHP plant were used for these examples. These estimates should be treated cautiously, Element Energy note (27) that a lack of high quality studies and numerous difficulties in arriving at their estimates mean the uncertainties in costs are likely to be greater than the differences between sectors.

Table 1. Reference capital costs (27) and derived 'Specific CAPEX' for a range of industrial emitters. Specific CAPEX is capital cost per unit of CO_2 capture capacity (see Section 2.2).

Industry	Reference captured CO_2	Adjusted total overnight costs	Specific CAPEX per unit of capture capacity CO_2
	Mt $^{-1}$ yr	£M, 2012	£ t(CO_2) $^{-1}$ yr
Refineries	0.81	220	272
Iron and steel large >3 Mt yr $^{-1}$	2.34	296	126
Iron and steel small <3 Mt yr $^{-1}$	0.09	35	389
Cement large >0.45 Mt yr $^{-1}$	0.66	127	192
Cement small <0.45Mt yr $^{-1}$	0.29	115	397
Lime	0.22	95	432
Ammonia	0.41	36	88
Hydrogen	0.23	33	143
Ethylene*	0.79	41	52
CHP small <0.2 Mt yr $^{-1}$	0.09	31	344
CHP medium 0.2-0.5 Mt yr $^{-1}$	0.25	60	240
CHP large >0.5 Mt yr $^{-1}$	0.59	110	186

* The calculated figure for the ethylene industry looks unduly low, the reference description suggests it should be related to costs for large CHP plant; hence that value (186 £ t(CO_2) $^{-1}$ yr) was used in further calculation in the present study.

However, since the Element Energy review (27) other industrial CCS project costs and estimates have become available which can help to benchmark the data used here. These include the Air Products Port Arthur project (29) and four projects costed by the Teesside Collective feasibility study: (30)

- Air Products, capture from large-scale hydrogen production (project CAPEX £269 M, capacity 1 Mt yr $^{-1}$ CO_2, 'Specific CAPEX' 269 £ t(CO_2) $^{-1}$ yr, exchange rate 1.6 USD/GBP, not indexed);
- BOC, capture from hydrogen production (project CAPEX £56 M, capacity 0.3 Mt yr $^{-1}$ CO_2, 'Specific CAPEX' 188 £ t(CO_2) $^{-1}$ yr);
- SSI Steelworks, capture from integrated power generation (project CAPEX £192 M, capacity 2.1 Mt yr $^{-1}$ CO_2, 'Specific CAPEX' 91 £ t(CO_2) $^{-1}$ yr);
- GrowHow, capture from ammonia production (project CAPEX £28 M, capacity 0.35 Mt yr $^{-1}$ CO_2, 'Specific CAPEX' 80 £ t(CO_2) $^{-1}$ yr);
- Lotte Chemicals, capture from small gas boiler (project CAPEX £35 M, capacity 0.05 Mt yr $^{-1}$ CO_2, 'Specific CAPEX' 700 £ t(CO_2) $^{-1}$ yr).

Although a power CCS project, costs from the Longannet FEED study (21) may also be compared, having a ‘Specific CAPEX’ of 299 £ t(CO_2) $^{-1}$ yr. While there are clear differences, these data suggest the values derived from the Element Energy review (27) form a reasonable basis for the estimates made in this study.

2.3 Pipeline connection distances and cost estimates

For selected emissions sites, potential routes and alternatives for connection to Feeder 8 or 10 were plotted and measured on Google Maps, taking account of geography (water bodies, urban areas) and existing pipeline corridors. (26),(31) Where practical, sharing of pipeline sections was assumed. Pipeline costs were estimated using a model published by the US National Energy Technology Laboratory (NETL), (32) which calculates materials, labour, right of way and miscellaneous costs as functions of pipeline length and diameter (costs were converted using an exchange rate of 1.6 USD/GBP but were not date indexed). Gas-phase transport in pipelines with diameters of 900 mm for shared sections and 500 mm for branch sections (nominal 36 and 20 inches respectively) were assumed for compatibility with the existing 900 mm Feeder 10. Where pipeline sections cross the Forth Estuary, the estimate for the crossing length was adjusted up by a factor of 4, derived from comparison between the NETL model and a ‘rule-of-thumb’ for terrain effects quoted in the NETL study. (32) Comparison of the NETL model with an alternative simpler cost model (33) gave good agreement on costs after compensating for exchange rate changes.

3 Results

3.1 Emission data distributions

SEPA’s pollution release inventory for 2014 includes records of 88 companies in Scotland with CO_2 emissions greater than the reporting threshold of 10,000 t yr $^{-1}$; the total emission from these sources was 19.2 Mt CO_2. The data are dominated by emissions from electricity generation (10.2 Mt, 53 %), in particular by emissions from the one remaining large coal-burning power station, Longannet, which alone released 9.2 Mt or 48 % of reported CO_2 emissions in 2014. Other than power, the industry sectors show a tapering distribution of CO_2 emissions as follows: refineries and gas treatment (3.7 Mt, 20 %), chemicals (1.9 Mt, 10 %), pulp, paper and board (1.1 Mt, 6 %), cement and glass (0.75 Mt, 4 %), environmental services (0.62 Mt, 3 %), food and drink (0.38 Mt, 2 %), with primary metals (0.16 Mt), mineral extraction (0.15 Mt) and manufacturing (0.07 Mt) each emitting less than 1 % of the total.

However, the closure of Longannet Power Station has been announced for 2016; (34) following this CO_2 emissions due to thermal power generation will be significantly lower and process industry sources will dominate Scottish point-sources emissions.

3.2 Location of emitters

The location map plotted for all the SPRI-listed sites with emission in 2014 above the reporting threshold, shows that the majority are situated in the Central Belt with other clusters in the north-east and around Dumfries in the south. Beyond these areas, a scatter of emitters from various industries includes only a few large emission sites.

In 2014, twenty-five sites in Scotland emitted more than 0.1 Mt CO_2. Their emission volumes and most locations are shown in Figure 1; locations in Shetland (Sullom Voe CHP and Oil Terminal), Orkney (Flotta Oil Terminal) and the Highlands (Lochaber Smelter) are not shown. Figure 1 also shows the routes of Feeder 10, which passes close to the cluster of large emitters in the Grangemouth and Forth Estuary areas, and of Feeder 8. The proposed Caledonia Clean Energy Project (CCEP), a coal-fuelled integrated gasification combined cycle power plant, is planned for a site in Grangemouth (not shown in Figure 1), close to the existing refinery (emitter 2 in Figure 1). It is anticipated to produce 3.8 Mt yr^{-1} CO_2 to be transported via Feeder 10 to storage in the North Sea. (35)

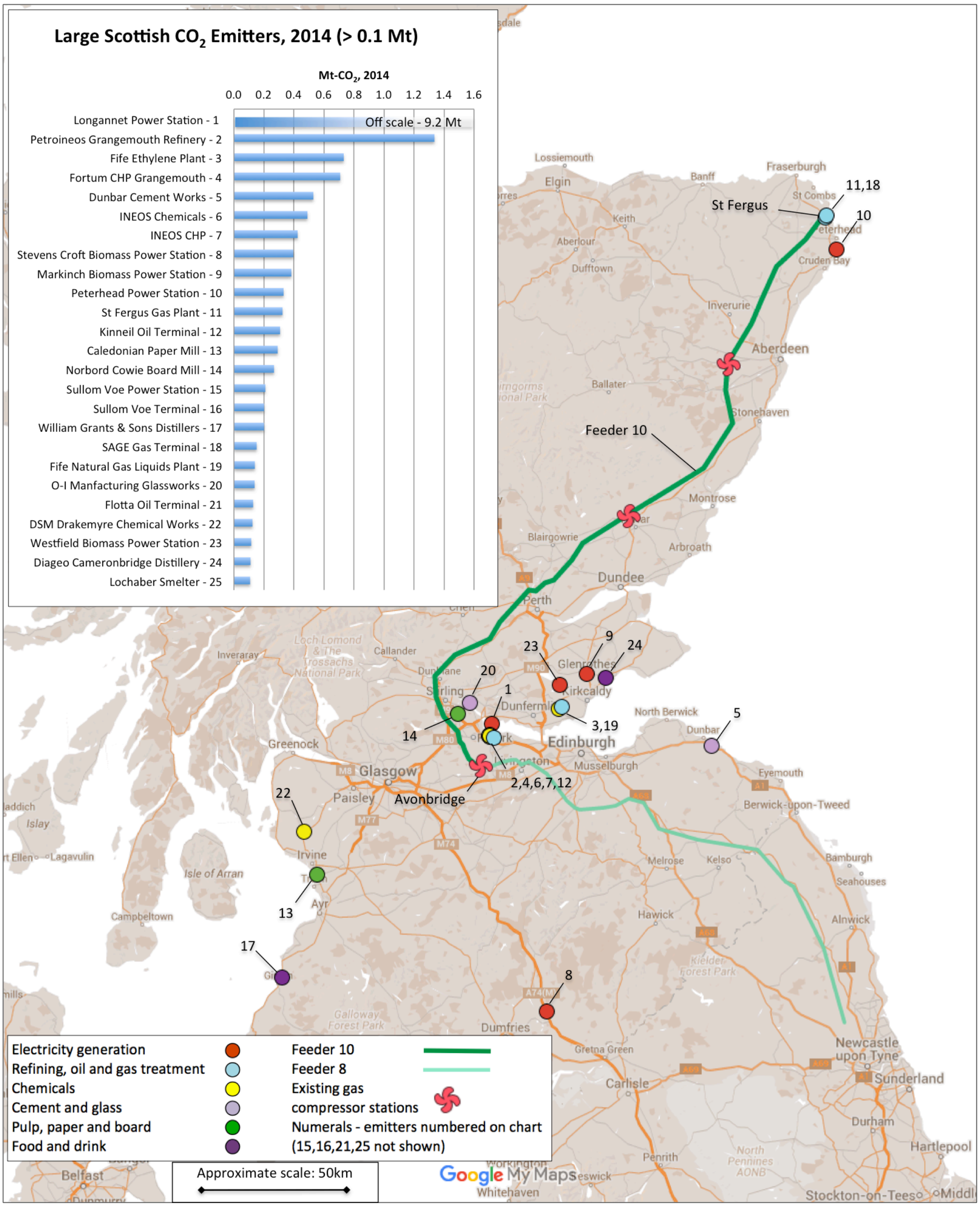

Figure 1. Scottish point-source emitters >0.1 Mt CO_2, 2014.

Route of Feeder 10 (dark green) and Feeder 8 pipeline (light green) also shown. Scotland's large industrial point sources of CO_2 emissions are favourably co-located with the Feeder 10 pipeline route suggesting its possible use as a trunk-line connecting Central Belt source clusters in Grangemouth and Fife to St Fergus for offshore CO_2 storage in the North Sea.

Considering the measured distance of each emitter from the routes of Feeders 8 or 10 allows an indication to be given of the potential importance of these existing pipelines to an integrated CCS network in Scotland. Of total point-source emissions in 2014 above the 10,000 t yr $^{-1}$ reporting threshold for CO_2, 88 % (16.8 Mt) were within 40 km of one of these pipelines and 80 % (15.3 Mt) were within 22 km. Removing data for Longannet Power Station from the analysis, leaves figures for 2014 of 77 % (7.6 Mt) of the remainder within 40 km and 62 % (6.2 Mt) within 22 km. The 40 km distance includes all major emitters in the centre and east of Scotland, but not those on the West Coast, Dumfriesshire, the Highlands and Islands. The 22 km distance includes the major hydrocarbon sites in Fife, as well as major emitters in the Forth Valley and Grangemouth areas.

3.3 Emitters selected for study

Sites were selected for further study of costs for capture plant and pipeline connection by combining the emission data analysis and the location analysis. The selection was made from the twenty-five largest emitters, listed in Figure 1. Sites selected were those likely to have on-going emissions that were located with a distance from Feeders 8 and 10 likely to be practical for pipeline connection and where use of these pipelines would be advantageous. Sites not meeting these criteria were Longannet Power Station (scheduled for closure 2016); (34) Peterhead Power Station and two large emitters sited at St Fergus (no benefit from using Feeder 10, though having potential for CO_2 capture and connection to offshore transport and storage infrastructure); and eight emitters sited more than 40 km from the feeder pipelines. The thirteen sites selected are listed in Table 2 together with their emissions in 2014, distances from Feeder 8 or 10 and derived data (see below).

3.4 Estimates of capture potential

The total CO_2 emission from these sites in 2014 was 5.68 Mt. Using the capture rates discussed in the methods section, the estimated annual capture potential was calculated for each emission site (Table 2). The data show that a total of around 4.2 Mt yr $^{-1}$ CO_2 could realistically be captured from these thirteen plants for emissions at 2014 levels.

This potential capture volume is slightly above the reported gas-phase CO_2 transport capacity of Feeder 10 of 3.5 Mt yr $^{-1}$, assuming entry-point compression only. (23) This capacity is considered to be available without major investment and is expandable to twice this capacity with investment on additional intermediate compression; this would allow other major projects, such as the proposed CCEP to use the pipeline also (see discussion in Section 4).

Table 2. Selected CO_2 emission sites, capture potential and CAPEX estimates

Emitting site (emitter number in Fig.1)	Emission 2014, Mt yr $^{-1}$	Distance from Feeder 8/10, km	Estimated capture rate	Estimated annual capture, Mt yr $^{-1}$	Specific CAPEX for capture, £ t(CO_2) $^{-1}$ yr	Estimated CAPEX, £M
Grangemouth cluster						
Petroineos Grangemouth Refinery (2)	1.34	10	0.45	0.60	272	163
Fortum CHP Grangemouth (4)	0.71	10	0.9	0.64	186	119
INEOS Chemicals (6)	0.49	10	0.45	0.22	272	60
INEOS CHP (7)	0.42	10	0.9	0.38	240	92
Kinneil Oil Terminal (12)	0.31	9	0.675	0.21	240	50
Fife and Upper Forth network						
Fife Ethylene Plant (3)	0.73	21	0.9	0.66	186	122
Markinch Biomass Power Station (9)	0.38	33	0.9	0.34	240	83
Norbord Cowie Board Mill (14)	0.27	4	0.9	0.24	240	58
Fife Natural Gas Liquids Plant (19)	0.14	22	0.675	0.09	344	32
O-I Manufacturing Glassworks (20)	0.14	10	0.9	0.12	344	43
Westfield Biomass Power Station (23)	0.12	29	0.9	0.10	344	36
Diageo Cameronbridge Distillery (24)	0.11	39	0.9	0.10	344	34
Other						
Dunbar Cement Works (5)	0.53	31	0.9	0.48	192	91
	Total 5.68			Total 4.19		

3.5 Estimates of capture costs

Order of magnitude cost estimates for CO_2 capture plant at the thirteen selected emitters were calculated from the estimated capture potential and the specific capital cost per tonne of CO_2 capture capacity derived above (Table 1). The 'Specific CAPEX' used and the resulting estimates of capture project CAPEX are given in Table 2.

3.6 Clustering options and cost estimates for pipeline networks

The position of the selected emission sites (shown in Figure 1) and their distances from Feeders 8 or 10 (Table 2) suggest options for linking potential capture units at these emitters into clusters connected by new collection networks to the existing pipelines.

The most obvious cluster is the Grangemouth petrochemicals complex comprising five major emitters: Petroineos Refinery, INEOS Chemicals, the two CHP stations that support these facilities (Fortum CHP Grangemouth and INEOS CHP) plus BP's Kinneil oil processing terminal. The CO_2 emissions from this cluster reported in 2014 totalled 3.27 Mt, with a potential capture quantity estimated here at around 2.1 Mt yr^{-1} CO_2. A potential pipeline route linking this Grangemouth cluster of emitters to Feeder 10 at the Avonbridge compressor station can be based on existing pipeline corridors. (26) This is estimated to require 15.5 km of shared trunk line plus about 2 km of branch lines to connect potential capture plant at the five selected sites. Capital cost for this network was estimated as £20 M using the NETL model (32) described in the methods section.

A second, looser, cluster of large emitters is present in central Fife, north of the Firth of Forth, comprising two petrochemical operations (Fife Ethylene Plant and Fife Natural Gas Liquids Plant), two biomass energy facilities (Westfield and Markinch Biomass Power Stations) and Diageo's Cameronbridge distillery. These sites emitted a total of 1.48 Mt CO_2 in 2014. Various routing options exist for connecting these emitters to Feeder 10. The route chosen for this study follows existing pipeline corridors (31) westwards to cross the River Forth near Alloa; this route would allow addition of the two large emitters sited near the upper Forth Estuary to this network (O-I Manufacturing glass works and the Norbord Cowie Board Mill). The total CO_2 emission from these seven sites was 1.88 Mt in 2014, with potential capture quantity estimated here at around 1.7 Mt yr^{-1} CO_2. The network would require approximately 30 km of collection branches and 42 km of shared trunk line, with capital cost estimated at £72 M using the NETL model, (32) including allowing for a 1 km river crossing.

The last of the thirteen selected sites, emitting 0.53 Mt CO_2 in 2014 with potential capture of around 0.5 Mt yr^{-1}, is the Dunbar cement works, situated in East Lothian remote from other large emitters. A stand-alone, 33 km link is one option to connect a capture plant at this site to Feeder 8. Estimating for this in 500 mm pipe using the NETL model (32) gives a cost of approximately £18 M. However, the availability of Feeder 8 for CO_2 transport has not been confirmed and no estimates of costs for its conversion are available.

These estimates serve to illustrate the advantage of the Grangemouth industrial cluster in terms of relatively low costs to transport a large volume of captured CO_2 to the existing pipeline, compared to higher costs for lower transported volumes from the more diffuse cluster of emitters in Fife. However, there are clearly other options for CO_2 transport from Fife that might be considered, such as shorter routes, but with longer river/sea crossings, to Grangemouth or to Feeder 8, or longer routes northwards to Feeder 10 without major water crossings. Alternatively, depending on other developments beyond the scope of this study, shipping of CO_2 from Fife, and from the Dunbar cement plant, might be an option.

In addition to the costs of a collection network and new link to the existing pipelines, there would be costs for refurbishing Feeder 10 and converting it for use with CO_2 between Avonbridge and St Fergus. These costs have been estimated by the Longannet project FEED study (21) at £79 M and it is assumed that users would share these costs in some manner to be agreed. This cost for refurbishment is substantially lower than the cost of building a new pipeline; using the NETL model, (32) the cost to replace the existing Feeder 10 with a pipeline of equivalent capacity between Avonbridge and St Fergus is estimated in the range £150-320 M, depending on design options.

3.7 Combined capture and transport costs

For the Grangemouth and Fife clusters identified, and the stand-alone option for the Dunbar cement plant, combining the estimated capital costs for capture of CO_2 and transport to St Fergus gives the following totals:

- Grangemouth cluster – £543 M for 2.1 Mt yr^{-1}.
- Fife cluster (including Upper Forth emitters) – £511 M for 1.7 Mt yr^{-1}.
- Dunbar cement plant – £119 M for 0.5 Mt yr^{-1}.

These totals include a share of the refurbishment cost for Feeder 10 in proportion to quantity of CO_2 transported, however, costs for use of Feeder 8 by Dunbar cement plant are not included as no estimates are available.

It should be emphasised that these costs are estimates of the initial capital expenditure only for the main elements of capture and transport, they are intended to indicate the scale of the ‘barrier to entry’ formed by the initial investment cost. They do not include operational costs or financing costs and do not indicate project lifetime total costs.

4 Analysis and Discussion

4.1 Analysis

The results above show that the main hydrocarbon processing and petrochemicals facilities at Grangemouth have the most favourable circumstances for establishing an industrial CO_2 capture cluster in Scotland. They have the greatest concentration of industrial emissions and connection routes to Feeder 10 would be fairly short, using existing pipeline corridors without major geographic barriers. Although the sites are complex, even a relatively low capture rate from the refinery, petrochemicals plant and oil terminal, together with more predictable, higher capture rates from on-site CHP facilities, could deliver a volume of CO_2 captured in the order of 2 Mt yr $^{-1}$. There would be scope to increase this through developing the capture network by adding capture to further emission points in the main sites or introducing capture projects at other, smaller emitters close by. This industrial cluster would also have strong synergy with the proposed CCEP CCS power project, which could link to the network with only a short additional section of pipeline (about 2 km).

Connection to Feeder 10 from capture projects at emitters in the Fife and Upper Forth areas with a new CO_2 network also appears attractive, but with greater connection distances involved and lower emissions it would be more expensive per volume captured and transported. There is also less scope for additional emitters to share the cost; there are no other large point-source emitters in the cluster area with the exception of Longannet power station. If Longannet were to be redeveloped as a thermal generating station (no present plans, 2016) there may be potential for sharing costs, although depending on the scale, this may require provision of additional transport capacity.

Given the advantages of location and existing infrastructure described, these two industrial CO_2 capture clusters and transport networks appear readily achievable and could deliver a meaningful reduction in Scottish emissions with a total of around 3.7 Mt yr $^{-1}$ CO_2 capture. This quantity represents just over 7 % of total Scottish greenhouse gas emissions (2013 basis) and 38.5 % of reported Scottish large point-source CO_2 emissions, excluding the main fossil fuel power stations (Longannet and Peterhead). There would be some scope to increase this capture quantity, particularly in the Grangemouth area.

This volume of CO_2 would take up the estimated capacity of Feeder 10 when reused for gas-phase transport without investment in additional intermediate compression. If that additional investment were made to double the capacity of Feeder 10 to 7 Mt yr $^{-1}$ CO_2, it would give capacity (within the accuracy of these estimates) for both the industrial capture networks and for the proposed CCEP, which plans to capture 3.8 Mt yr $^{-1}$ CO_2. This project would fit well with the potential Grangemouth industrial capture cluster, in terms of both the position of the site to share costs of new pipelines and in sharing the capacity of Feeder 10. This would suggest that a coordinated approach and negotiated method of sharing investment in pipeline costs might be necessary to avoid unfairly penalising specific projects. Given the uncertainty of timing in the need to upgrade Feeder 10 capacity, even in a favourable environment for

CCS projects, it would be useful if a modular approach to upgrading Feeder 10 capacity could be used, for instance by adding new intermediate compression stations sequentially. It should be noted that the suggestion of a gas phase CO_2 capture network is relevant here due to the existence of the Feeder 10 pipeline, which is limited to carrying CO_2 in the gas phase. However, if both a new trunk line and a new collection network were needed costs would most likely be lower if designed for liquid CO_2 conditions.

4.2 Scenarios for cluster development

A number of scenarios can be envisaged by which industrial CCS in Central Scotland and the proposed CCEP CCS power project could be developed together, using the existing pipeline, Feeder 10, for transport of CO_2 to St Fergus with onward offshore transport and storage in the North Sea. Given the limitations of the pipeline capacity, and the potential for its expansion (23) it is useful to examine how the pipeline might best be utilised.

Figure 2 shows estimated CO_2 capture quantities for four scenarios of industrial CCS development, each with and without the addition of the first proposed phase of CCEP development, set against the potential capacity limitations of Feeder 10 with sequential investment in expansion.

The four scenarios in Figure 2 are:

1. The Grangemouth industrial CCS cluster at the restricted capture rates described above, taken as a baseline.
2. The Grangemouth industrial CCS cluster with overall capture rates from the five largest emitters developed to average 90 % of total emissions.
3. Scenario 1 with the addition of the Fife and Upper Forth network described above.
4. Scenario 2 combined with the Fife and Upper Forth network.

Each scenario is shown as option (a) for volume without CCEP, and option (b) including the proposed capture volume of CCEP.

Examining Figure 2 suggests that fully developing opportunities for industrial CCS between the Grangemouth cluster and the Fife/Upper Forth network may require some improvement in capacity of Feeder 10 over its nominal, un-boosted capacity of 3.5 Mt yr $^{-1}$ CO_2. Adding capture from CCEP to the system would immediately require expansion of the pipeline capacity above this level for all industrial CCS scenarios and, for those with both clusters included, would require a capacity above the optimum suggested, although within the maximum theoretical capacity of 10 Mt yr $^{-1}$ for gas-phase transport of CO_2 in Feeder 10. (23)

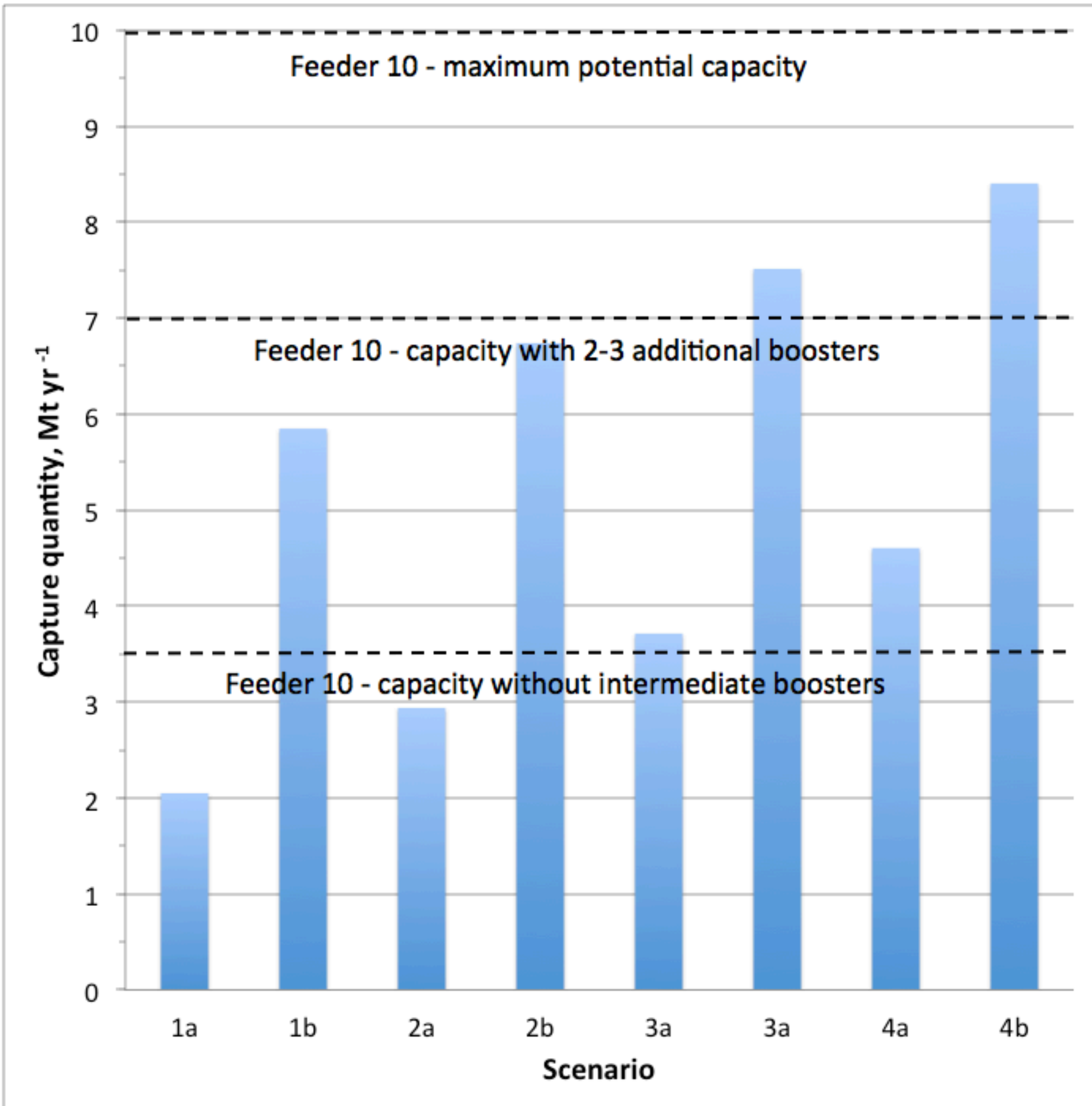

Figure 2. Scenarios for CO_2 capture totals and thresholds for CO_2 transport capacity of Feeder 10.

Scenario 1a Grangemouth cluster, restricted capture rates; 2a Grangemouth cluster, 90 % capture from main emitting sites; 3a, 4a scenario 1a, 2a respectively plus Fife/Upper Forth network; scenario 1b, 2b, 3b, 4b scenario 1a, 2a, 3a, 4a respectively plus Caledonia Clean Energy Project Phase 1.

Feeder 10 capacity thresholds: 3.5 Mt yr $^{-1}$ with entry-point compression only; 7 Mt yr $^{-1}$ optimised with intermediate boosting; 10 Mt yr $^{-1}$ maximum theoretical capacity. (23)

4.3 Comparison with other cluster proposals

It is useful to compare the situation of the Central Scotland industrial clusters with the other leading CCS industrial clusters, namely Rotterdam and Teesside, under consideration in Europe. Both have a larger concentration of industrial emissions in the immediate cluster area than Grangemouth. (15),(30) Rotterdam is planning for an offshore CO_2 pipeline from the port area to a storage site fairly close offshore. Teesside has not selected a preferred storage target, with connection to sites in the Southern or Central North Sea both discussed. Central Scotland is not immediately local to an offshore storage site, but the existence of Feeder 10, available at low cost for conversion to CO_2 transport, means it is not at a disadvantage compared to these other areas and presents an excellent opportunity for CCS cluster development.

This further suggests value in investigating the potential for converting gas supply pipelines in other regions of Europe for CO_2 transport connecting clusters of emitters to storage sites. This could be particularly relevant for inland emitters where new pipeline development could prove controversial and costly. Such an approach might facilitate more rapid CCS deployment as gas supply pipelines typically connect areas of high emissions to gas producing regions where depleted fields, existing subsurface knowledge and higher chance of public acceptance increase the likelihood of efficient and cost-effective CO_2 storage delivery. (36)

4.4 Implications of results for decarbonisation

The total indicative capital cost for these capture and transport infrastructure developments, at around £1 billion (Section 3.7), leading to CO_2 emissions reduction of around 4 Mt yr $^{-1}$, appears competitive with current investment to enable expansion in low-carbon renewable capacity. For example, the recently completed (2015) Beauly to Denny power transmission line facilitating expansion of renewable generation in highland Scotland at a capital cost of around £800 million enables power generation emissions reduction of around 1-2 Mt yr $^{-1}$ CO_2.

To date, major CCS projects in the EU have not secured investment. EU capital support grants have been allocated, but the low and unstable EU Emissions Trading System carbon price, which for industrial emitters is partially derogated, has not given appropriate incentive to invest. Feed-in-Tariff subsidies for low-carbon electricity generation have been proposed, primarily in the UK, but no funding model for industrial CCS has been developed. A recent analysis (37) prepared for the Teesside Collective feasibility study favoured two models: an 'Emitter Contract-for-Difference', in essence a low-carbon production premium using a subsidy adjusted against the carbon price; and a 'Storage Driven' approach, where a transport and storage infrastructure provider (or 'market maker' (38)) charges a usage fee to emitters based on CO_2 volume handled.

In both cases, funding for the development of CO_2 infrastructure should recognise the wider, long-term benefit of the investment and not be assessed solely as part of a single project or an early-stage cluster. Here, UK electricity transmission developments provide a practical example: they are funded from a system-wide levy rather than having costs allocated solely to the generator or consumer who immediately benefits. In recognition of its importance, funding for CO_2 infrastructure development should follow a similar model, perhaps by hypothecating a relevant proportion of the nationally retained carbon tax revenues.

The development of industrial CCS is crucial to achieving economy-wide decarbonisation in line with Scottish, UK and EU mitigation targets, and global climate mitigation ambitions. Early regional support and investment in industrial CCS could protect the economic and social value of existing energy- and carbon-intensive industries that are expected to become increasingly exposed to emissions reduction policies as EU carbon market reforms are enacted (39) and carbon markets introduced in other major economic regions. (40) The provision of industrial CCS infrastructure leveraging the existing pipeline asset in Central Scotland could provide a regional advantage in allowing early, low-carbon industrial development and attracting investment from industries looking to reduce their exposure to emissions liabilities.

Moreover, the combination of Feeder 10 onshore and the existing offshore infrastructure give a unique importance to the deployment of industrial CCS in Central Scotland, beyond its local regional impact, owing to the role this has in unlocking the commercial development of the European-scale storage resource in the Central North Sea. In initial stages CO_2 from continental Europe would most economically and flexibly be delivered by ship. Peterhead port has been favourably assessed for development of a CO_2 import terminal, (41) and direct ship delivery to offshore offloading facilities has also been suggested. (42) Longer-term, subject to sufficient demand, pipelines could be developed connecting major storage formations to continental export hubs. (43)

5 Conclusions

CCS is widely recognised as a technology necessary to achieve, at least cost, regional, national and EU targets for CO_2 emission reduction. The Central North Sea is considered to be a major resource for CO_2 storage, but outwith Norway, CCS projects have yet to be delivered. This study explores and calculates indicative costs for the use of the existing Feeder 10 natural gas pipeline, already evaluated for CO_2 transport, to facilitate the formation of a CCS cluster in Scotland. We identify a potential capture volume of 4.2 Mt yr^{-1} CO_2 from thirteen selected industrial sites, amounting to 74 % of the total emission of these sites, which are large emitters located <40 km from Feeder

10 in Fife, the Firth of Forth area and at the Grangemouth petrochemicals complex.

Capital costs of carbon capture plant at individual sites are estimated ranging from £32-163 M, giving a total of £983 M for all thirteen sites. Capital costs for pipeline connections to Feeder 10 are estimated considering two collection networks, one for Grangemouth (£20 M) and one connecting emitters in Fife and the upper Forth area (£72 M). The previously estimated cost of refurbishing Feeder 10 for CO_2 transport is £79 M, compared to a replacement cost estimated here of £150-320 M.

The scale of CO_2 capture potential from industry is found to be compatible with the basic capacity of Feeder 10. Known options for expansion of Feeder 10 capacity, by provision of intermediate compression facilities, could accommodate increased CO_2 volumes from improved capture efficiency or connection of additional industrial sites. This expansion of pipeline capacity could also allow both the industrial capture networks assessed here and the planned Caledonia Clean Energy CCS power project to use Feeder 10, giving a possible total CO_2 capture of 8 Mt yr^{-1}.

This work shows that the presence of an existing pipeline available for reuse with CO_2 can bring direct savings to CCS projects. It also shows that the capital costs due to transport infrastructure form a relatively small proportion (10-20 %) of the total when several projects share costs. Combined with the presence of existing offshore infrastructure available for reuse with CO_2 in the North Sea and the potential for value generation through CO_2 utilisation in enhanced oil recovery (not detailed in this work) these factors make a strong case for initiating a CO_2 capture cluster and transport network development in Central Scotland.

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